

Low braking index of PSR J1734-3333: an interaction between fall-back disk and magnetic field?

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ABSTRACT

Recent timing observation reported that the radio pulsar PSR J1734 - 3333 with a rotating period $P = 1.17$ s is slowing down with a period derivative $\dot{P} = 2.28 \times 10^{-12} \text{ s s}^{-1}$. Its derived braking index $n = 0.9 \pm 0.2$ is the lowest value among young radio pulsars with the measured braking indices. In this Letter, we attempt to investigate the influence of the braking torque caused by the interaction between the fall-back disk and the strong magnetic field of the pulsar on the spin evolution of PSR J1734 - 3333. Analytical result show that this braking torque is obviously far more than that by magnetic dipole radiation for pulsars with spin period of > 0.1 s, and play an important role during the spin-down of the pulsars. Our simulated results indicate that, for some typical neutron star parameters, the braking index and the period derivative approximately in agreement with the measured value of PSR J1734 - 3333 if the material inflow rate in the fallback disk is $2 \times 10^{17} \text{ g s}^{-1}$. In addition, our scenario can account for the measured braking indices of four young pulsars. However, our predicted X-ray luminosity are 1 -2 order of magnitude higher than the observation. We proposed that this discrepancy may originate from the instability of fall-back disk.

Key words: pulsars: individual (PSR J1734 - 3333) – stars: neutron – stars: evolution – pulsars: general

1 INTRODUCTION

Radio pulsars are believed to be rapid rotating, strongly magnetized neutron stars, which originated from the core collapse of massive stars during supernova explosions (Pacini 1967). By magnetic dipole radiation or charged particle winds, pulsars lose rotational kinetic energy, and their spin periods gradually increase (Gold 1968). In the diagram of pulse period (P) versus period derivative (\dot{P}), normal radio pulsars locate a concentrated region, which has periods of ~ 1 s and period derivatives of $10^{-16} - 10^{-14} \text{ s s}^{-1}$ (Manchester 2004). Recent timing observation reported that radio pulsar PSR J1734 - 3333 with a rotating period $P = 1.17$ s is slowing down with a relatively high period derivative $\dot{P} = 2.28 \times 10^{-12} \text{ s s}^{-1}$ (Espinoza et al. 2011). It is exciting that this source has a lowest braking index $n = \Omega \dot{\Omega} / \dot{\Omega}^2 = 0.9 \pm 0.2$ (where $\Omega = 2\pi/P$) among young pulsars with the measured braking indices.

The braking index of pulsars is determined by the slow-down torque. If the magnetic fields of pulsars are constant, magnetic dipole radiation predicted the braking index $n = 3$.

However, all the measured braking indices for young radio pulsars are less than 3. Blandford & Romani (1988) suggested that the variation of magnetic moment may cause $n < 3$. The braking torque caused by the magnetic dipole radiation and the unipolar generator may produce the braking indices of 1 - 3 (Xu & Qiao 2001). Tauris & Konar (2001) argued that the exponential models for magnetic field decay and alignment can account for the observed data. Adopting a magnetic field evolution model, Zhang & Xie (2012) can interpret all the observed statistical properties of the braking indices of the pulsars in Hobbs, Lyne & Kramer (2010). Furthermore, other braking torques may result in the braking indices $n < 3$. As a dominant spin-down torque, strong relativistic winds give rise to $n = 1$ (Michel 1969). The propeller torque caused by a fall-back disk of pulsars may be responsible for the low braking index (Alpar, Ankay & Yazgan 1988; Menou, Perna & Hernquist 2001). The tidal torque originated from the gravitational interaction between the pulsar and the fall-back disk can lead to the observed braking indices (Chen & Li 2006). Recently, Magalhaes, Miranda & Frajuca (2012) have modified canonical model to explain the observed braking indices ranges,

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and then predicted the possible values of the braking indices of several other young pulsars.

The relatively small braking index of PSR J1734 - 3333 challenges the present braking theories of pulsars. Assuming that the magnetic field and the particle luminosity are both constants, this source may be braking by a rotation-powered particle wind (Espinoza et al. 2011; Tong et al. 2013). Adopting a modified formula for the propeller torque, a self-similar fall-back disk can account for the small braking index, P, \dot{P} of PSR J1734 - 3333 (Liu et al. 2014). Using the same model that used to study the evolution of anomalous X-ray pulsars and soft gamma-ray repeaters (Ertan et al. 2009; Alpar, Ertan & Çalişkan 2011), a fall-back disk around PSR J1734 - 3333 can fit the observed period, the first and second period derivatives, and the X-ray luminosity of this source (Çalişkan et al. 2013).

In this Letter, the braking torque caused by the interaction between the strong magnetic field and the fall-back disk around the pulsar is applied to investigate the evolution of PSR J1734 - 3333. In section 2, we describe the theoretical model of interaction between the magnetic field and the fall-back disk. In section 3, the calculated results for PSR J1734 - 3333 and other six pulsars with known braking indices are presented. Finally, we summarize the results with a brief discussion in section 4.

2 MODEL

A small amount of fall back material may form a debris disk (the so-called fall-back disk) around the radio pulsars because all the mass could not be fully ejected during the supernova explosion (Michel 1988). The brightest known AXP 4U 0142+61 was detected the mid-infrared emission, which hints the existence of a fall-back disk (Wang et al. 2006). Recently, the counterpart to AXP 1E 2259+586 at 4.5 μm can be interpreted by a X-ray-heated fall-back disk (Kaplan et al. 2009). PSR J1734-3333 is a young radio pulsar, and may associated with the supernova remnant G354.8-0.8 (Manchester et al. 2002). It is possible that this source will evolve to the magnetars region after about 30 kyr (Espinoza et al. 2011). Therefore, PSR J1734-3333 may have a fall-back disk that has not yet been detected.

During the evolution of pulsars, the braking torque originating from the magnetic coupling between the magnetic field and the fall-back disk should play an important role. The magnetic field lines of the pulsar could penetrate the fall-back disk, and then twist due to the differential rotation between the pulsar and the disk (Ghosh & Lamb 1979a,b). The resulting magnetic torque (N_{mag}) would transfer angular momentum between the pulsar and the disk, and spin down or up the pulsar. The magnetic torque N_{mag} depends on the "fastness parameter" $\omega = \Omega/\Omega_{\text{m}}$, where $\Omega, \Omega_{\text{m}}$ are the angular velocity of the pulsar and the inner radius of the fall-back disk, respectively. In this work, the inner radius of the fall-back disk is taken to be the magnetosphere radius

$$R_{\text{m}} = 1.6 \times 10^8 \left(\frac{B}{10^{12} \text{G}} \right)^{4/7} \left(\frac{\dot{M}}{10^{18} \text{g s}^{-1}} \right)^{-2/7} \text{cm}. \quad (1)$$

For radio pulsar, accretion process can not occur, and the magnetosphere radius is larger than the co-rotation radius

$R_{\text{co}} = (GM/\Omega^2)^{1/3}$. Therefore, $\Omega > \Omega_{\text{m}}$, and the "fastness parameter" $\omega > 1$. Adopting some typical assumptions, the magnetic torque can be written as (see also Dai & Li 2006)

$$N_{\text{mag}} = \frac{\dot{M} \sqrt{2GMR_{\text{m}}}}{3} \left(\frac{2}{3\omega} - 1 \right), \quad (2)$$

where G is the gravitational constant, M the mass of the pulsar, \dot{M} the mass inflow rate in the fall-back disk.

We assume that PSR J1734-3333 is a radio pulsar with a normal magnetic field. Its total braking torque consists of magnetic dipole radiation and the magnetic torque, i. e.

$$I\dot{\Omega} = N_{\text{dip}} + N_{\text{mag}}, \quad (3)$$

where I is the momentum of inertia of the pulsar. The torque caused by the magnetic dipole radiation

$$N_{\text{dip}} = -\frac{2B^2 R^6 \sin^2 \theta}{3c^3} \Omega^3, \quad (4)$$

where B, R are the surface magnetic field, and the radius of the pulsar, respectively; θ is the inclination of the magnetic axis with respect to the rotation axis of the pulsar.

3 RESULTS

Adopting some typical parameters for the pulsar as follows, $B = 10^{12} \text{G}$, $\theta = \pi/2$, $M = 1.4 M_{\odot}$, $R = 10^6 \text{cm}$, we have $N_{\text{dip}} = -2.47 \times 10^{28} \text{g cm}^2 \text{s}^{-1} \Omega^3$. If the mass inflow rate in the fall-back disk $\dot{M} = 1 \times 10^{17} \text{g s}^{-1}$, we can derived $R_{\text{m}} = 3.09 \times 10^8 \text{cm}$, $\Omega_{\text{m}} = 2.5 \text{s}^{-1}$, and $N_{\text{mag}} = -1.1 \times 10^{34} (1 - 5.0/(3\Omega)) \text{g cm}^2 \text{s}^{-2}$. In figure 1, we plot the braking torque of the pulsars as a function of the spin period. It can be clearly seen that, for nascent pulsars with a rapid spin, the braking torque by magnetic dipole radiation is dominant. With the spin-down, the magnetic torque gradually exceed the magnetic dipole radiation torque at $P \approx 0.08 - 1.1 \text{ms}$, and then dominate the spin-down of pulsars.

3.1 PSR J1734-3333

It is clear that, $|N_{\text{mag}}| \gg |N_{\text{dip}}|$ for PSR J1734-3333, hence we can neglect the torque caused by the magnetic dipole radiation. Assuming that the mass inflow rate in the fall-back disk and the magnetic field are constant, the braking index of PSR J1734-3333 is given by

$$n = \frac{\ddot{\Omega} \Omega}{\dot{\Omega}^2} = \frac{2\Omega_{\text{m}}}{3\Omega - 2\Omega_{\text{m}}}. \quad (5)$$

The period derivative can be written as

$$\dot{P} = -\frac{N_{\text{mag}} P^2}{2\pi I}, \quad (6)$$

and the second order period derivative is

$$\ddot{P} = \frac{2\dot{P}^2}{P} - \frac{\sqrt{2GMR_{\text{m}}}\dot{M}}{3I} \frac{2\Omega_{\text{m}}}{3\Omega^2} \dot{P}. \quad (7)$$

Table 2 summarizes the calculated braking index, \dot{P} , and \ddot{P} for PSR J1734 - 3333. As $\dot{M} = 2 \times 10^{17} \text{g s}^{-1}$, the predicted braking index can fit the observation. However, there exist $\sim 10\%$ and 50% errors between the predicted values and the observations for \dot{P} , and \ddot{P} , respectively.

Table 2. Main results of the fall-back disk model for PSR J1734 - 3333.

$\dot{M}(\text{g s}^{-1})$	$R_m(\text{cm})$	$\Omega_m(\text{s}^{-1})$	$\dot{P}(\text{ss}^{-1})$	$\ddot{P}(\text{ss}^{-2})$	n
1×10^{17}	3.09×10^8	2.5	1.70×10^{-12}	3.8×10^{-24}	0.45
2×10^{17}	2.53×10^8	3.4	2.57×10^{-12}	7.2×10^{-24}	0.73
3×10^{17}	2.26×10^8	4.0	3.18×10^{-12}	8.7×10^{-24}	0.99
5×10^{13}	2.71×10^9	0.097	3.59×10^{-15}	2.2×10^{-29}	0.57

Table 1. Observed and derived parameters for PSR J1734 - 3333.

Parameter	Value
$P(\text{s})$	1.17
$\dot{P}(\text{ss}^{-1})$	2.28×10^{-12}
$\ddot{P}(\text{ss}^{-2})$	$5.0 \pm 0.8 \times 10^{-24}$
Characteristic age (kye)	8.1
Surface magnetic field (G)	5.2×10^{13}
Braking index, n	0.9 ± 0.2

3.2 Other pulsars with known braking indices

In order to test our model, we also calculated the braking indices of other six pulsars in Table 3. Figure 1 shows that, for pulsars with spin period $\lesssim 0.1$ s the braking torque by magnetic dipole radiation cannot be ignored. Therefore, we can derived the general braking index from equation (3)

$$n = 3 - \frac{S(\frac{8\Omega_m}{3\Omega} - 3)}{-K\Omega^3 + S(\frac{2\Omega_m}{3\Omega} - 1)}, \quad (8)$$

where $K = 2B^2 R^6 \sin^2 \theta / (3c^3)$, $S = \dot{M} \sqrt{2GM R_m} / 3$. Taking the typical parameters of pulsars, $K = 2.47 \times 10^{28} \text{ g cm}^2 \text{ s}$, and S can be derived by the mass inflow rate \dot{M} in the fall-back disk.

Figure 2 plots the evolutionary paths in the braking indices vs. spin periods of pulsars surrounded by a fall-back disk. Since magnetic dipole radiation is the dominant spin-down mechanism, the braking indices of pulsars with rapid spin ($P \lesssim 0.03$ s when $\dot{M} \sim 10^{17} \text{ g s}^{-1}$, and $P \lesssim 0.3$ s when $\dot{M} \sim 10^{13} - 10^{14} \text{ g s}^{-1}$,) are very near 3. With the sharp increase of the magnetic torque, the braking index firstly decrease to a minimum of 0.2 at $P \sim 0.2 - 0.6$ s when $\dot{M} \sim 10^{17} \text{ g s}^{-1}$, and then sharply increase in the last stage. To compare with observations, we also show the locations of seven pulsars with known braking indices by the solid squares in Figure 2. As shown in this figure, our simulated results can roughly fit the observed braking indices of four pulsars when $\dot{M} \sim 10^{17} \text{ g s}^{-1}$. For a lower mass inflow rate $\dot{M} \sim 10^{13} - 10^{14} \text{ g s}^{-1}$, our simulation can approximately account for the braking indices of PSR J1734 - 3333 and other 3 pulsars. However, the magnetic torque $N_{\text{mag}} \propto \dot{M}^{6/7}$, so the inferred \dot{P} and \ddot{P} of PSR J1734 - 3333 are obviously lower than the observation (see Table 2). Table 3 shows that the period derivative of other three pulsars are also $\sim 10^{-12} \text{ ss}^{-1}$. Therefore, it is difficult for the fall-back disk with a low mass inflow rate to explain the braking process of pulsars.

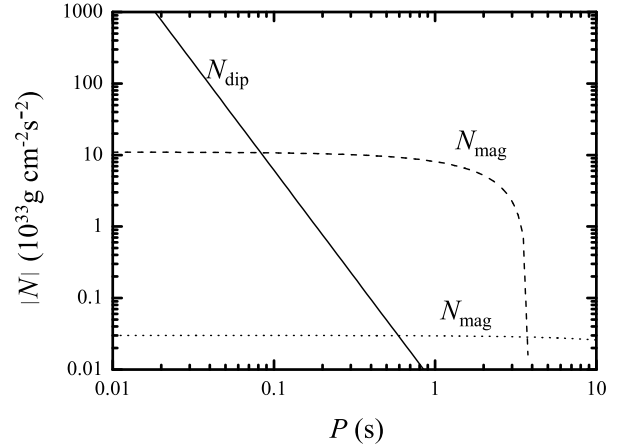

Figure 1. Braking torques of pulsars as a function of the spin period. The solid, dashed, and dotted curves denote the braking torque caused by magnetic dipole radiation and the magnetic torques when the mass inflow rate in the fall-back disk $\dot{M} = 1 \times 10^{17}, 1 \times 10^{14} \text{ g s}^{-1}$, respectively.

Table 3. Spin periods and braking indices for seven pulsars.

Pulsar	P (s)	\dot{P} (10^{-12} ss^{-1})	n	Reference
Crab	0.0334	0.42	2.509	1
PSR B0540-69	0.0505	0.48	2.14	2,3
Vela	0.0893	0.13	1.4 ± 0.2	4
PSR B1509-58	0.151	1.5	2.837	2
PSR J1846-0258	0.327	7.1	2.16	5
PSR J1119-6127	0.408	4.0	2.684	6
PSR J1734-3333	1.17	2.3	0.9 ± 0.2	7

Reference. (1) Lyne, Pritchard & Graham Smith (1993); (2) Livingstone et al. (2007); (3) Boyd et al. (2006); (4) Lyne et al. (1996); (5) Livingstone et al. (2011); (6) Waltevrede, Johnston & Espinoza (2011); (7) Espinoza et al. (2011).

4 DISCUSSION AND SUMMARY

In this Letter, we proposed an alternative scenario to interpret the low braking index of PSR J1734-3333. In our opinion, this pulsar should has a normal magnetic field. However, it may be surrounded by a fall-back disk, and the magnetic torque originating from the magnetic coupling between the magnetic field and the fall-back disk can efficiently brake

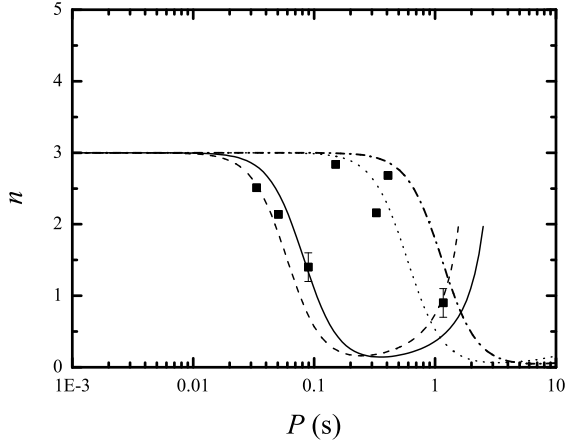


Figure 2. Braking index of pulsars as a function of the spin period. The solid, dashed, dotted, and dashed-dotted curves represent the braking index when the mass inflow rate in the fall-back disk $\dot{M} = 1 \times 10^{17}$, 3×10^{17} , 10^{14} , and 10^{13} g s^{-1} respectively. The solid squares represent seven pulsars with known braking indices.

the pulsar. Our calculations show that, for PSR J1734-3333 the magnetic torque is obviously far more than the braking torque by magnetic dipole radiation. When the material inflow rate in the fallback disk is $2 \times 10^{17} \text{ g s}^{-1}$, our calculated braking index and period derivative approximately in agreement with the measured value.

However, our scenario present a relatively high X-ray luminosity. The X-ray luminosity of the fall-back disk can be calculated by $L_X \sim \frac{GM\dot{M}}{2R_m} \approx 7.4 \times 10^{34} \text{ erg s}^{-1}$, which is obviously higher than the inferred X-ray luminosity (0.5 - 10 keV, $0.1 - 3.4 \times 10^{33} \text{ erg s}^{-1}$) of PSR J1734-3333 (Olausen et al. 2010). This discrepancy may originate from the instability of fall-back disk. The inflow plasma with not enough kinetic energy can not escape from the system, and build-up in the disk (D’Angelo & Spruit 2010, 2011, 2012), which experienced short outbursts separated by long quiescent intervals (similar to transient X-ray source). In a recurrent period, the average angular velocity derivative $\dot{\Omega} = \dot{\Omega}_h d + \dot{\Omega}_l (1-d)$, here d is the duty cycle, and $\dot{\Omega}_h, \dot{\Omega}_l$ can be derived by equation (3) when the pulsar is in high state and low state, respectively. The constant mass inflow rate adopted in section 3 is the average value in a recurrent period. Therefore, the spin evolution of the pulsar is mainly influenced by the mass inflow rate in high state. The mass inflow rate in low state with long interval is very low, and the neutron star can be observed as a radio pulsar. If so, PSR J1734 - 3333 may be a intermittent pulsar.

Our model is also applied in other six pulsars with known braking indices. Including PSR J1734-3333, our predicted braking indices can fit the observed values of four pulsars. However, our calculations show that pulsars with $P \sim 0.2 - 0.6 \text{ s}$ and normal magnetic field ($\sim 10^{12} \text{ G}$) may have ultra-low braking indices of ~ 0.2 . We expect further detailed radio observations for pulsars to confirm or negate our idea in the future. It is noticed that our scenario cannot fit the observed braking indices of other three pulsars. We suspect they may have relatively strong magnetic fields. Some pulsars might be born with strong magnetic

fields or enhance their magnetic fields by strong glitches (Lin & Zhang 2004).

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